Evidence for Orbital Decay of RX J1914.4+2456: Gravitational Radiation and the Nature of the X-ray Emission

Tod E. Strohmayer

Laboratory for High Energy Astrophysics, NASA's Goddard Space Flight Center, Greenbelt, MD 20771; stroh@clarence.gsfc.nasa.gov

ABSTRACT

RX J1914.4+2456 is a candidate double-degenerate binary (AM CVn) with a putative 569 s orbital period. If this identification is correct, then it has one of the shortest binary orbital periods known, and gravitational radiation should drive the orbital evolution and mass transfer if the binary is semi-detached. Here we report the results of a coherent timing study of the archival ROSAT and ASCA data for RX J1914.4+2456. We performed a phase coherent timing analysis using all observations spanning an ≈ 4.6 year period. We demonstrate that all the data can be phase connected, and we present evidence that the 1.756 mHz orbital frequency is increasing at a rate of $8 \pm 3 \times 10^{-18}$ Hz s^{-1}, consistent with the expected loss of angular momentum from the binary system via gravitational radiation. In addition to providing evidence for the emission of gravitational waves, measurement of the orbital $\dot{\nu}$ constrains models for the X-ray emission and the nature of the secondary. If stable mass accretion drives the X-ray flux, then a positive $\dot{\nu}$ is inconsistent with a degenerate donor. A helium burning dwarf is compatible if indeed such systems can have periods as short as that of RX J1914.4+2456, an open theoretical question. Our measurement of a positive $\dot{\nu}$ is consistent with the unipolar induction model of Wu et al. which does not require accretion to drive the X-ray flux. We discuss how future timing measurements of RX J1914.4+2456 (and systems like it) with for example, Chandra and XMM-Newton, can provide a unique probe of the interaction between mass loss and gravitational radiation. We also discuss the importance of such measurements in the context of gravitational wave detection from space, such as is expected in the future with the LISA mission.

Subject headings: Binaries: general - Stars: individual (RX J1914.4+2456) - Stars: white dwarfs - cataclysmic variables - X-rays: stars - X-rays: binaries

1. Introduction

The evolution of highly compact binary stars is driven to a large extent by the interplay between angular momentum loss from gravitational radiation and mass transfer between the components (see, for example Rappaport, Joss & Webbink 1982). Detailed study of the orbital evolution of such systems can thus provide a unique physical laboratory for the study of gravitational radiation and its effects on binary evolution.

The shortest period cataclysmic variables (CVs), the AM CVn stars, are the most compact binaries known, with orbital periods < 40 minutes. Many may be double-degenerate systems (see Warner 1995 for a review). Their formation is complex, depending on unstable mass transfer leading to common envelope (CE) evolution, processes which are not well understood (see Nelemans et al. 2001a). Such systems likely begin as a pair of main sequence stars, each of 3 - 5 $M_{\odot}$. After perhaps two episodes of CE evolution a pair of white dwarfs separated by only a few $R_{\odot}$ remain. Gravitational radiation losses eventually bring the pair closer until the smaller mass star begins to fill its Roche lobe. The minimum period (at contact) of such a system depends on the details of the constituents, but it may be as short as 5-6 minutes (Tutukov & Yungelson 1996; Hils & Bender 2000).

Theoretical studies by Tutukov & Yungelson (1996) and more recently, Nelemans et al. (2001a) suggest that as many as $\sim 10^8$ double-degenerate systems may populate the Galaxy. Because of their compact nature, these objects are ideal targets for space based gravitational wave detection with the Laser Interferometer Space Antenna (LISA) mission. They are likely the progenitors of at least some type Ia supernovae and may also represent a substantial fraction of supersoft X-ray sources (see Hils & Bender 2000; Nelemans, Yungelson & Portegies Zwart 2001b). Their evolution has also been proposed as a channel for production of millisecond radio pulsars via accretion induced collapse (see Savonije, de Kool, & van den Heuvel 1986). An understanding of their formation, evolution and properties is therefore crucial to many areas of active astrophysical investigation.

The recent discovery of two double-degenerate binary candidates, RX J1914.4+2456 with a period of 569 s, and RX J0806+15 with a period of 321 s, has sparked keen interest in these objects (see Israel et al. 1999; Israel et al. 2002; Ramsay, Hakala & Cropper 2002). RX J1914.4+2456 (hereafter RX J1914) was discovered in the ROSAT all-sky survey. Motch et al. (1996) found that the X-ray flux is modulated with a period of $\approx$ 569 s, and concluded that the source was likely an intermediate polar (IP), with the 569 s period reflecting the spin of the white dwarf primary. However, subsequent ROSAT observations did not find any additional periods such as are commonly present in IPs. This, combined with the unusual 100% X-ray modulation, led Cropper et al. (1998) to suggest that the source is a double-degenerate polar. Polars, systems containing an accreting strongly magnetized white dwarf,

rotate synchronously with the orbital period. If this identification is correct, RX J1914 has one of the shortest binary orbital periods known. If the orbital period is 569 s, and the secondary fills its Roche lobe, it must be a helium star, and perhaps a degenerate He white dwarf. Savonije et al. (1986) predict a minimum period of 636 s for a non-degenerate helium burning secondary, which, given the theoretical uncertainties, may not be long enough to completely rule out a non-degenerate secondary as argued by Cropper et al. (1998).

The X-ray spectrum of RX J1914 is soft, with a 40 eV blackbody model providing an acceptable fit to the ROSAT PSPC data (Motch et al. 1996; Cropper et al. 1998). The X-ray luminosity is in the range 4×10^{33} to 1×10^{35} ergs s^{-1} for an assumed distance of 100 to 400 pc. Accretion at a rate of $\sim 1 \times 10^{-8} M_{\odot}$ yr^{-1} could conceivably power the X-ray flux. Ramsay et al. (2000) detected the optical counterpart to RX J1914. It is modulated in the V, R, and I bands at the 569 s period, but the optical peak leads the X-ray peak by about 0.4 cycles. This strengthens the orbital identification for the 569 s period. No other periods are seen in the optical data. More recent spectroscopy by Ramsay et al. (2002) reveals a line-free spectrum and no detectable polarization, inconsistent with its identification as a polar. If the source is indeed a polar, then the lack of polarization and emission lines is puzzling. Alternatively, Marsh & Steeghs (2002) have recently suggested that the primary may be non-magnetic and accretion takes place via direct impact of the accretion stream (i.e., a double-degenerate Algol). An alternative not requiring accretion has been proposed by Wu et al. (2002). They suggest the system might be a unipolar inductor, with the secondary moving through the magnetic field of the primary because of a small asynchronism between the orbit and primary spin (in analogy with the Jupiter - Io system). This sets up an electric field which can drive currents in the magnetosphere, providing the energy for the X-ray emission. Most recently, Norton, Haswell & Wynn (2002) have suggested that the system may be a stream-fed IP viewed nearly face-on. If this hypothesis is correct, then the orbital period is not seen directly, and the observed X-ray periodicity is the beat period between the spinning white dwarf primary and the orbital period.

Without any additional information it is difficult to determine which, if any, of the current hypotheses regarding the nature of RX J1914 is correct. However, strong clues to the nature of the X-ray flux could be obtained if the orbital evolution of the system can be detected. Indeed, for conservative mass transfer it is relatively straightforward to show that if the donor star is a degenerate dwarf, then stable mass transfer can only proceed with a widening of the orbit and a decrease in the orbital frequency (see Nelemans et al. 2001a; Savonije et al. 1986). Thus, a measurement of the rate of change of the orbital frequency can provide a way to break the model degeneracy outlined above.

This possibility has led us to reinvestigate the available timing data on RX J1914, with

the goal of trying to detect or constrain orbital frequency changes in the system. Here we report the results of our timing analysis of the ROSAT and ASCA observations of RX J1914 over a period of ≈ 4.6 years. We find evidence for an increase in the orbital frequency of the system at a rate of $\approx 8 \times 10^{-18}$ Hz s^{-1}, which is similar to that expected from gravitational radiation losses if the observed X-ray period is indeed the orbital period.

The plan of this paper is as follows. In §2 we describe in detail our phase coherent timing study of the ROSAT and ASCA data. We show that all the data can be phase connected and that a positive $\dot{\nu}$ is strongly indicated. In §3 we discuss the implications of our findings for the nature of the X-ray emission from RX J1914 and show that orbital decay argues against accretion as the source of the X-ray flux unless the donor is non-degenerate. We conclude in §4 with a summary of our principal findings and plans for continued precision timing of such objects, and the synergy of such measurements with future space-based gravitational wave detection.

2. Data Extraction and Analysis

A total of ≈ 100 ksec of observing time on RX J1914 was obtained with ROSAT and ASCA over the period from September, 1993 to April, 1998. Of the six observations, one was with the ROSAT Position Sensitive Proportional Counter (PSPC), four were ROSAT High Resolution Imager (HRI) pointings, and the most recent observation was with the ASCA Solid-State Imaging Spectrometer (SIS). These data are now all in the public HEASARC archive. A number of studies of some or all of these data have been presented in the literature. Motch et al. (1996) discovered the 569 s modulation. Cropper et al. (1998) and Ramsay et al. (2000) have also reported timing results for RX J1914. Ramsay et al. (2000) used all the available ROSAT data, in addition to the single ASCA pointing and found that they could phase-connect all the data to within ≈ 0.02 cycles using a constant frequency model.

Table 1 gives a log of the observations used in our study. We used the HEASARC FTOOLS data analysis package (i.e., XSELECT) to extract and analyse the data. We began by producing images and extracting source events. We extracted events from circular regions around the point source centroid using radii consistent with the relevant point spread functions of each instrument. In all cases the point source was easily identified and there were no source confusion problems. For example, Figure 1 shows the HRI image obtained from the April 30, 1996 observation (26 ksec exposure).

We next applied barycentric corrections to the event times for each observation. We used the standard mission ftools in conjunction with the ROSAT and ASCA orbital and

JPL (DE200) solar system ephemerides (Standish et al. 1992). For the source position we used the coordinates, ($\alpha = 19^h14^m26.1^s$, $\delta = 24°56'43.6''$:J2000), obtained by Ramsay et al. (2002) from their study of the optical-infrared counterpart to RX J1914. The ROSAT tool *abc*, which computes the X-ray event times at the solar system barycenter, also corrects for the spacecraft clock drift. With the drift removed, the ROSAT clock is typically stable to a few 10s of milliseconds. Even a clock error of a 100 milliseconds between observing epochs corresponds to only a 1.8×10^{-4} cycle error for RX J1914. Thus, the ROSAT times are more than precise enough for our purposes. Hirayama et al. (1996) estimate the ASCA absolute timing precision to be on the order of 2 ms. Moreover, Saito et al. (1997) found the stability of the ASCA clock frequency on a timescale T to be, $\delta f/f < 3 \times 10^{-8}(T/10^4 \text{ s})^{-1}$. This level of drift would produce a fractional phase shift during the ASCA observation of only $< 1 \times 10^{-6}$. These numbers indicate that the ASCA timing capability is at least as good as the expected ROSAT precision, and is more than sufficient for our timing study of RX J1914. Our extraction of source events from the six observations resulted in a total of 4315 photons.

2.1. Coherent Timing Methods

We performed our coherent timing studies using the Z_n^2 statistic (Buccheri 1983; see also Strohmayer & Markwardt 2002 for an example of the use of this statistic in a similar context). In our study we performed model fitting in two complementary ways; a total power method, and a phase fitting method similar to those used in pulsar timing studies. Although both methods use the same data, the total power method does not directly utilize the phase information. We perform both analyses in order to provide a means of double checking our results and to have a level of “redundancy,” however, the phase timing method uses all the available information (both magnitude and phase) and we generally will describe our quantitative results in terms of this technique.

For the total power method we evaluate;

$$Z_n^2 = \frac{2}{N} \sum_{k=1}^{n} \left[\left(\sum_{j=1}^{N} \cos k\phi_j \right)^2 + \left(\sum_{j=1}^{N} \sin k\phi_j \right)^2 \right] , \tag{1}$$

where $\phi_j = 2\pi \int_0^{t_j} \nu(t')dt$, $\nu(t')$ is the frequency evolution model, t_j are the observed X-ray event times, N is the total number of X-ray events, and n is the number of harmonics included in the sum. With this method we vary the timing model parameters in order to maximize the total Z_n^2 power.

For our phase timing analysis we begin by defining the complex vector

$$C_n = \sum_{k=1}^{n} \left(\sum_{j=1}^{N} \cos k\phi_j + i \sum_{j=1}^{N} \sin k\phi_j \right) . \tag{2}$$

The phase angle, ψ is then defined as

$$\psi = \tan^{-1} \left[\frac{\sum_{k=1}^{n} \sum_{j=1}^{N} \sin k\phi_j}{\sum_{k=1}^{n} \sum_{j=1}^{N} \cos k\phi_j} \right] . \tag{3}$$

To perform a phase timing fit we break up the X-ray event times into a set of M bins and compute the phase angle ψ_l for each bin. The phases are simply given by;

$$\psi_l = \tan^{-1} \left[\frac{\sum_{k=1}^{n} \sum_{m} \sin k\phi_m}{\sum_{k=1}^{n} \sum_{m} \cos k\phi_m} \right] , \tag{4}$$

where the index m runs over all events in bin l. We then compute

$$\chi^2 = \sum_{l=1}^{M} \left(\psi_l - \psi_{avg} \right)^2 / \sigma_{\psi_l}^2 , \tag{5}$$

where ψ_{avg} is the average phase angle computed from all M bins. To find the best fitting model, we vary the timing parameters and search for those which yield the minimum χ^2. For a coherent signal the error σ_{ψ_l} in the phase angle is given simply by $1/\sqrt{(Z_n^2)}$.

In modelling the ROSAT and ASCA event times we use a two parameter frequency model; $\nu(t) = \nu_0 + \dot{\nu}(t - t_0)$, where ν_0, $\dot{\nu}$ and t_0 are the orbital frequency at t_0, the orbital frequency derivative, and the reference epoch, respectively. With this model the phase advance due to $\dot{\nu}$ has the well known quadratic time dependence; $\Delta\phi = \frac{1}{2}\dot{\nu}(t - t_0)^2$.

2.2. Theoretical Expectations

For a detached binary with a circular orbit the rate of change of the orbital frequency due to gravitational radiation is (see for example, Evans, Iben & Smarr 1987; Taylor & Weisberg 1989)

$$\dot{\nu}_{gr} = 1.64 \times 10^{-17} \left(\frac{\nu}{10^{-3}\ \text{Hz}} \right)^5 \left(\frac{\mu}{M_\odot} \right) \left(\frac{a}{10^{10}\ \text{cm}} \right)^2 \ \text{Hz s}^{-1} , \tag{6}$$

where, ν, μ, and a are the orbital frequency, reduced mass and orbital separation of the components, respectively. Given the 569 s orbital period of RX J1914, and likely scenarios

for the binary components, a total system mass of $\lesssim 1M_\odot$ and reduced mass of $\mu \approx 0.05M_\odot$ are likely (see Cropper et al. 1998; Wu et al. 2002). With these numbers, Kepler's law gives an estimate of the orbital separation $a \approx 1 \times 10^{10}$ cm. This leads to an estimate of $\dot{\nu}_{gr} \approx 1 \times 10^{-17}$. A $\dot{\nu}$ of this size would produce a total phase advance of ≈ 0.1 cycles over the four year timespan of the data. We note again that this is much larger than any anticipated errors associated with drift of the ROSAT or ASCA clocks.

As noted earlier orbital evolution involves the interplay between mass transfer and angular momentum loss to gravitational radiation. Indeed, for conservative mass transfer it is relatively straightforward to show that if the donor star is a degenerate dwarf, then stable mass transfer can only proceed with a widening of the orbit and a decrease in the orbital frequency (see Nelemans et al. 2001a; Savonije et al. 1986). If there is no mass transfer then one would expect the orbital frequency to increase (positive $\dot{\nu}$). In either case the *magnitude* of the orbital frequency evolution is set by $\dot{\nu}_{gr}$ above.

2.3. Results

We began our analysis by conducting a total Z_n^2 power search using the constant frequency model ($\dot{\nu} = 0$). We searched in a frequency range around the known 0.00659 day (1.756 mHz) period reported by Ramsay et al. (2000), and we sampled with a resolution substantially finer than the anticipated frequency resolution of $1/T$, where T is the total timespan of the data (about 4.6 years). We found a best frequency of $1.7562467 \times 10^{-3} \pm 2 \times 10^{-10}$ Hz, which is consistent with the constant frequency found by Ramsay et al. (2000).

By varying n we found that most of the signal was in the fundamental and first harmonic, so for the remainder of our analysis we fixed $n = 2$. Figure 2 shows the Z_2^2 power spectrum in the vicinity of our best period. Note the multiple side-lobe peaks which result from the sparse sampling (i.e., time gaps). Since the sampling is so sparse it is crucial to investigate the range of both ν and $\dot{\nu}$ which could conceivably fit the data. In order to bound the phase space in which to make a coherent search with all the data we first computed a frequency history by analysing each observation individually. We then fit the individual time - frequency measurements to a linear frequency evolution model. We found that the frequency history is well fit by a constant frequency ($\dot{\nu} = 0$) model, but that solutions with a range of ν and $\dot{\nu}$ are also statistically acceptable. To determine the search range of ν and $\dot{\nu}$ we found the 3σ confidence ranges for each parameter from the frequency history fit. These considerations indicate that acceptable solutions are only possible within the following limits; 1.7553×10^{-3} Hz $< \nu < 1.7578 \times 10^{-3}$ Hz, and -1.7×10^{-14} Hz s^{-1} $< \dot{\nu} < 9.0 \times 10^{-15}$ Hz s^{-1}.

We next performed a grid search using all the data, sampling the range of ν and $\dot{\nu}$ found above from the time - frequency measurements. For each ν - $\dot{\nu}$ pair we calculated the total power Z_2^2 statistic as well as the χ^2 statistic using the phase timing method. For the χ^2 search we made phase measurements in all the good time intervals which were at least 400 s long. This resulted in a total of 59 phase measurements. Our best solution has $\chi^2 = 62.5$ with $\nu = 1.7562465 \times 10^{-3}$ Hz, and $\dot{\nu} = 8 \times 10^{-18}$ Hz s^{-1}. Within the range of phase space searched there is only one other remotely plausible candidate solution. It has a $\chi^2 = 73.9$ with $\nu = 1.7570585 \times 10^{-3}$ Hz, and $\dot{\nu} = -1.0265 \times 10^{-14}$. The magnitude of the implied frequency derivative for this solution is orders of magnitude larger than expected for either gravitational radiation driven orbital decay or accretion-induced spin up of a white dwarf. These facts, combined with its substantially larger χ^2, suggest that it can be excluded on astrophysical grounds and that it likely represents an "alias" of the best solution produced by the sparse sampling. Although we think this conclusion is fairly secure, it will require future timing measurements to test it definitively.

Figure 3 shows contours of constant $\Delta\chi^2$ versus ν and $\dot{\nu}$ from our phase fitting analysis in the vicinity of our best solution. The results strongly favor a positive $\dot{\nu} = 8 \pm 3 \times 10^{-18}$ Hz s^{-1}. The quoted uncertainty on $\dot{\nu}$ is the 1σ, two-parameter confidence region. The results from the total Z_2^2 power method are entirely consistent with the phase fitting method, but in the interests of space we only show the $\Delta\chi^2$ contours. We obtained a minimum χ^2 of 62.5, which for 57 degrees of freedom (dof), indicates that the data are consistent with the model. With $\dot{\nu} \equiv 0$ we have a $\Delta\chi^2 = 11.5$, which excludes $\dot{\nu} = 0$ at the 99.7% confidence level. Table 2 summarizes our best timing solution.

In Figure 4 we show the phase residuals from our best solution. The abscissa corresponds to phase measurement number (time ordered). The rms residual is 0.026 cycles and is indicated by the dashed horizontal lines. Measurements from the 6 different observations (see Table 1) are denoted by the vertical dotted lines. We next used our best fitting χ^2 model parameters to phase fold all the data. Figure 5 compares the phase folded profiles from each individual observation. The average profile using all the data is also shown as the bottom trace. The profiles are more or less consistent within the errors, thus it seems unlikely that pulse profile variations could have a significant influence on our timing analysis.

3. Implications and Discussion

We have found strong evidence for an increase in the putative orbital frequency of RX J1914, however, processes other than gravitational radiation might also exert torques on the system that could produce orbital period variations. In the remainder we discuss some of the

issues regarding interpretation of the observed period evolution as well as the implications for the nature of RX J1914.

3.1. Interpretation and Caveats

Orbital period variations at the level of $\Delta\nu/\nu \lesssim 1 \times 10^{-5}$ have been observed in a number of close binaries (see Warner 1988; Applegate 1992; and references therein). These variations, typically observed over timescales of decades or longer, have been ascribed to magnetic activity of the low mass component (see Hall 1991; Applegate 1992; Arzoumanian, Fruchter & Taylor 1994). In particular, the presence of conditions necessary to produce a stellar dynamo; convection and differential rotation, appear to be essential in producing such variations (Applegate 1992). Applegate (1992) argues that in such systems the observed $\Delta\nu/\nu$ can be produced by a change in the quadrupole moment of the magnetically active star. If a change in the mass quadrupole is responsible for the observed orbital period variation in RX J1914, then it must have a magnitude $(\Delta q/m_2R^2) = (\dot{\nu}\Delta T/9\nu_0)(a/R)^2 \approx 4 \times 10^{-6}$, where for simplicity we have assumed the companion radius, R, is equal to the Roche lobe radius, and we have used the well known relation between orbital separation and Roche lobe radius (see for example Paczynski 1967).

If RX J1914 is indeed a double-degenerate, then any type of standard magnetic activity is not expected and it would seem unlikely that such an effect could be responsible for the observed $\dot{\nu}$. However, non-degenerate, helium burning secondaries can develop surface convection zones (see Savonije et al. 1986), which might arguably support a dynamo and drive a magnetic activity cycle. Orbital period changes due to magnetic activity are also necessarily accompanied by substantial optical luminosity variations (of order 0.1 mag). Although there does not appear to be any direct evidence for such optical variations, and we regard this scenario as unlikely, we cannot at present definitively rule it out. One way to do so will be to obtain long term X-ray monitoring of the orbital period, as well as further optical - infrared monitoring. Such observations will test our derived timing ephemeris and, if confirmed, will enable a secure association of the observed $\dot{\nu}$ with gravitational radiation. Additional clues would come from a constraint on $\ddot{\nu}$. If the only torque acting is gravitational radiation, then it should have a characteristic magnitude $\ddot{\nu} \approx 4 \times 10^{-31}$ Hz s^{-2}. If a $\ddot{\nu}$ term much greater than this is detected, then it will indicate the presence of additional torques in the system.

3.2. Orbital Evolution

As mentioned above, the orbital evolution has important implications for the nature of mass transfer in close binaries. If one assumes that the system angular momentum is dominated by the orbital motion, and if one also imposes the assumptions of conservative mass exchange and angular momentum loss only from gravitational radiation, then it is relatively straightforward to show that the mass accretion rate, $\dot{m}_2$, and orbital frequency derivative, $\dot{\nu}$, are given by the following expressions (see for example, Rappaport, Joss & Webbink 1982; Nelemans et al. 2001a);

$$\dot{m}_2 = -1.72\times10^{-7} \left(\frac{m_2}{M_\odot}\right) \left(\frac{\mu}{M_\odot}\right) \left(\frac{a}{10^{10}\ \mathrm{cm}}\right)^2 \left(\frac{\nu}{10^{-3}\ \mathrm{Hz}}\right)^4 \left(\frac{1}{\left(\frac{\xi(m_2)}{2} + \frac{5}{6} - q\right)}\right) \ M_\odot\ \mathrm{yr}^{-1} , \tag{7}$$

and

$$\dot{\nu} = -8.21 \times 10^{-18} \left(\frac{\mu}{M_\odot}\right) \left(\frac{a}{10^{10}\ \mathrm{cm}}\right)^2 \left(\frac{\nu}{10^{-3}\ \mathrm{Hz}}\right)^5 \left(\frac{\left(\frac{1}{3} - \xi(m_2)\right)}{\left(\frac{\xi(m_2)}{2} + \frac{5}{6} - q\right)}\right) \ \mathrm{Hz\ s}^{-1} . \tag{8}$$

Here, m_2 is the mass of the donor star, $q \equiv m_2/m_1$ is the mass ratio ($q < 1$), and $\xi(m_2) = \frac{m_2}{r}\frac{dr}{dm_2}$, is the dimensionless derivative of the radius of the donor, r, with respect to its mass. It can be shown that stable mass transfer requires, $\frac{\xi(m_2)}{2} + \frac{5}{6} > q$ (see, for example, Rappaport, Joss & Webbink 1982). If the mass transfer is stable, the only way to have $\dot{\nu} > 0$, as observed, is for $\xi(m_2) > 1/3$. This argues against degenerate donors since these stars grow as they lose mass and $\xi(m_2) < 0$.

If the orbital decay results only from gravitational radiation losses and there is no mass transfer, then the constraint on $\dot{\nu}$ implies a constraint on the so called "chirp mass,"

$$\left(\frac{M_{ch}}{M_\odot}\right)^{5/3} = \left(\frac{\mu}{M_\odot}\right) \left(\frac{m_1 + m_2}{M_\odot}\right)^{2/3} = 2.7 \times 10^{16} \left(\frac{\nu}{10^{-3}\ \mathrm{Hz}}\right)^{-11/3} \dot{\nu} . \tag{9}$$

This constraint follows directly from equation (6) and the use of Kepler's law to substitute for the orbital separation, a. We show in Figure 6 the mass constraint derived from our $\dot{\nu}$ measurement. The solid contour denotes the constraint for our best fit, while the dashed contours mark the 1σ, two-parameter confidence limits. The inferred component masses are similar to those deduced by other researchers (see Ramsay et al. 2000; Wu et al. 2002; Marsh & Steeghs 2002).

3.3. The Nature of the X-ray Flux

Perhaps the simplest interpretation for the observed X-ray flux is that it is accretion-driven (see, for example, Cropper et al. 1998; Ramsay et al. 2000). However, in the most straightforward accretion scenario, stable mass transfer would require that the donor be non-degenerate for reasons outlined above. Thus, our measurement of a positive $\dot{\nu}$ favors a non-degenerate donor if accretion powers the X-ray flux.

An alternative, proposed recently by Wu et al. (2002), is that the X-ray flux is powered by a unipolar inductor mechanism similar to that which is thought to operate between Jupiter and Io (Clarke et al 1996). In this model the donor sits inside its Roche lobe and no accretion takes place. An asynchronism between the orbital period and the spin of the secondary, on the order of a part in 10^{-3}, would produce a voltage drop sufficient to account for the X-ray luminoisty. In this scenario, both electrical and gravitational dissipation will cause the orbital frequency to increase, although gravitational losses dominate for most reasonable choices of the component masses (see Wu et al. 2002). Thus, this model is consistent with our $\dot{\nu}$ measurement. A criticism of the model is that the lifetime of the unipolar inductor phase should be relatively short as synchronization should occur in ~ 1000 yr (see Wu et al. 2002; Marsh & Steeghs 2002), unless some additional torque acts to hold the system out of synchronization. An example of a compact binary system which may be held out of synchronization is the "black widow" pulsar PSR B1957+20. This object shows orbital period variations somewhat similar to those seen in magnetically active close binaries (Arzoumanian, Fruchter & Taylor 1994). Applegate & Shaham (1994) suggest that a wind driven from the companion by pulsar irradiation drives a torque which acts to keep the system asynchronized. This leads to tidal dissipation which powers a wind from the companion and may also be responsible for the magnetic activity. Although this model does not appear directly applicable to RX J1914, it does suggest that other processes can maintain asynchronism over long timescales.

Recently, Marsh & Steeghs (2002) have proposed that RX J1914 is a "double-degenerate Algol," accreting by direct impact of the accretion stream onto the primary. They argue that this model strongly favors a double-degenerate scenario for formation of AM CVn systems. In this model the components are not magnetized and the spins are not necessarily synchronized, however, the X-ray source associated with impact of the stream is fixed in the rotating orbital reference frame. A positive $\dot{\nu}$ argues against this scenario for RX J1914 unless the donor is non-degenerate. A degenerate donor might still be viable if the mass transfer has gone unstable and formed a common envelope which is responsible for the observed orbital decay. However, this idea would appear to suffer from the same problem as the unipolar inductor model, that is, the lifetime of this phase would be short. Moreover, at some point the X-

ray flux would become obscured by the envelope. If more complete theoretical investigations firmly rule out all non-degenerate donors because of the short orbital period then our positive $\dot{\nu}$ measurement would provide evidence for a unipolar induction mechanism for RX J1914.

Although the interpretation of the 569 s period as the orbital period seems most plausible, it is conceivable that the observed period is the spin period of an intermediate polar (IP), and that the orbital period has simply not been detected yet. Norton, Caswell & Wynn (2002) have recently proposed such a scenario for RX J1914. They suggest that the system is a stream-fed IP viewed nearly face-on.

If the system is an IP, then one would expect the orbital period to be longward of the 569 s spin period. Empirically, the spin and orbital periods of IPs satisfy $P_{orb} \approx 10P_{spin}$, so that an orbital period of ≈ 100 minutes would be reasonable. The mass donor in such a system would have a mass $\approx 0.1M_{\odot}$, implying an orbital separation, $a \approx 1R_{\odot}$. Such an orbit would introduce a phase delay to the white dwarf spin of at most a few seconds, which is much smaller than the phase offset implied for our best fit $\dot{\nu}$, so that the orbital modulation of a putative white dwarf spin would be negligible. If the primary white dwarf is accreting then it will experience a characteristic spin-up torque of magnitude,

$$N = \dot{m}\,(G\ M\ r_m)^{1/2}\ , \tag{10}$$

where r_m is the radius at which the accreting matter gets attached to the magnetic field of the primary. This torque will produce a characteristic spin-up rate,

$$\dot{\nu} = 7.97 \times 10^{-17}\ \left(\frac{\dot{m}}{10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}}\right)\left(\left(\frac{M}{M_{\odot}}\right)^{-1}\ \left(\frac{R}{10^{-2}\ R_{\odot}}\right)^{-3}\right)^{1/2}\ \mathrm{Hz\ s}^{-1}, \tag{11}$$

where for simplicity we have assumed r_m is equal to the white dwarf radius, R. Interestingly, this $\dot{\nu}$ is not far from the observed value and can be made consistent with a reasonable choice of $\dot{m}$. Thus, the observed $\dot{\nu}$ is not inconsistent with the IP model proposed by Norton, Caswell & Wynn (2002). Although orbital period variations in a truly face-on system would be very hard to detect, a further test of their hypothesis would be to probe deeper for an as yet unseen orbital period longward of the 569 s period. Such a search would ideally be made by Chandra or XMM-Newton, whose wide, eccentric orbits will provide better sensitivity than previous satellites hampered by the nature of the low Earth orbit observing window.

3.4. Gravitational Waves

If the orbital period of RX J1914 is indeed 569 s, then its compact nature would make it a prime source of gravitational radiation for space-based detection. Its gravitational wave

frequency $2\nu_{orb} = 3.51$ mHz is within the most sensitive frequency range of the proposed LISA interferometer (see Armstrong, Estabrook & Tinto 2001), and is at high enough frequency to be outside the likely source confusion band produced by Galactic compact binaries (see Nelemans, Yungelson & Portegies Zwart 2001b). The inferred strain amplitude for such systems, $\approx 1 \times 10^{-21}$, is well above the predicted LISA noise floor at this frequency. Indeed, a detection of a gravitational wave signal at twice the observed X-ray frequency would definitively rule out the IP models proposed for RX J1914.

If our timing solution is correct, then the phase advance due to $\dot{\nu}$ is approaching 0.3 cycles, which can be easily confirmed with continued X-ray timing of the system, for example, with Chandra and XMM-Newton. If confirmed such observations will provide a much more accurate measurement of $\dot{\nu}$. Future monitoring will also establish if the observed $\dot{\nu}$ is related to the orbital period variations seen in magnetically active binaries.

The combination of future X-ray timing and direct gravitational wave measurements of systems like RX J1914 would provide a powerful new probe of gravitational radiation and binary evolution. The X-ray measurements will directly aid future detection of the system by space-based interferometers, such as LISA. Measurement of the orbital frequency derivative combined with detection from space of the time dependence of the gravitational wave amplitude will provide the source distance (Schutz 1996). Moreover, the direct measurement of both orbital decay and the gravitational wave luminosity will provide new insights into the dynamics of orbital evolution in close binaries.

3.5. Summary

We have presented evidence that the 1.756 mHz X-ray frequency of RX J1914 is increasing at a rate of 8×10^{-18} Hz s^{-1}. This rate is consistent with that expected from gravitational radiation losses in a detached compact binary and close to that expected given the likely scenarios which have been presented for the constituent masses of RX J1914. If the X-ray emitting star were accreting from a degenerate donor, then one would naively expect the orbit to be widening and the frequency decreasing, in conflict with the observations. This suggests that accretion may not power the X-ray flux, as proposed recently by Wu et al. (2002), who suggest a unipolar induction mechanism as the source of the X-rays. Alternatively, a non-degenerate helium burning secondary would be consistent with the observed $\dot{\nu}$; however, it may be that such systems cannot achieve such a short orbital period. Finally, an IP identification remains possible, if the system is nearly face-on. If this is the case, then the observed frequency increase likely reflects the accretion-induced spin up of the white dwarf primary. Although we favor the gravitational radiation orbit decay interpretation,

other compact, magnetically active binaries have shown orbital period variations at a level similar to the implied orbital frequency change in RX J1914. It will have to wait for future monitoring of the orbit to completely rule out this possibility.

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Figure Captions

Fig. 1.— A portion of the ROSAT HRI image of RX J1914.4+2456 from the 1996 April 30 observation. The grey-scale indicates counts in each pixel. the pixels are 4" on a side.

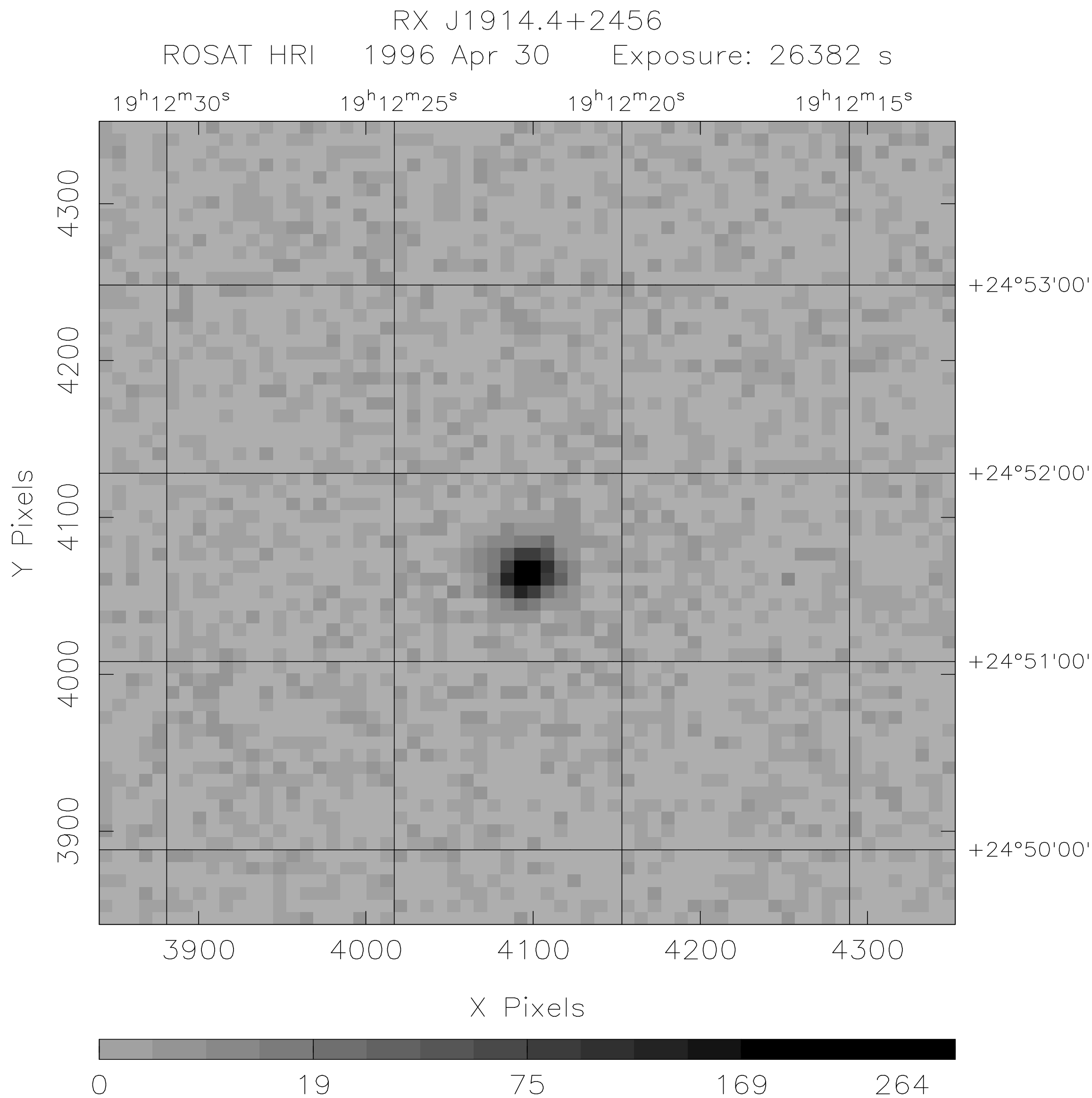
Fig. 2.— Power density spectrum computed using the Z_2^2 power statistic, and $\dot{\nu} = 0$. The multiple side-lobe peaks result from the sparse sampling (i.e., temporal gaps) of the time series. However, as discussed in detail in the text, the sampling is sufficient to resolve any cycle count ambiguities, that is, all the sub-peaks are significantly below the central peak.

Fig. 3.— Summary of our phase timing grid search for ν and $\dot{\nu}$. Shown is the map of constant $\Delta\chi^2 \equiv \chi^2 - min(\chi^2)$ in the vicinity of our best timing solution. Here, $\nu_0 \equiv 1.7562465 \times 10^{-3}$ Hz. For $\Delta\chi^2$ we show contours at 1, 3, 6, 9, and 12. The best fitting parameters are marked with the triangle symbol.

Fig. 4.— Phase residuals (cycles) using the best fit parameters from minimizing χ^2. The rms residual is 0.026 cycles and is indicated by the dashed horizontal lines. The abscissa corresponds to phase measurement number (time ordered). Measurements from the 6 different observations (see Table 1) are denoted by the vertical dotted lines.

Fig. 5.— Phase folded pulse profiles for each individual observation, using our best χ^2 solution. Each profile has been normalized to an amplitude of 1 and has been shifted vertically by 1 for clarity. Each observation is labelled with its start date (see also Table 1).

Fig. 6.— Constraints on the component masses from our $\dot{\nu}$ measurement. The solid curve denotes the constraint for the best fitting $\dot{\nu}$, and the dashed contours denote the 1σ confidence interval. The constraint was derived assuming no mass transfer and gravitational radiation as the only angular momentum loss mechanism.



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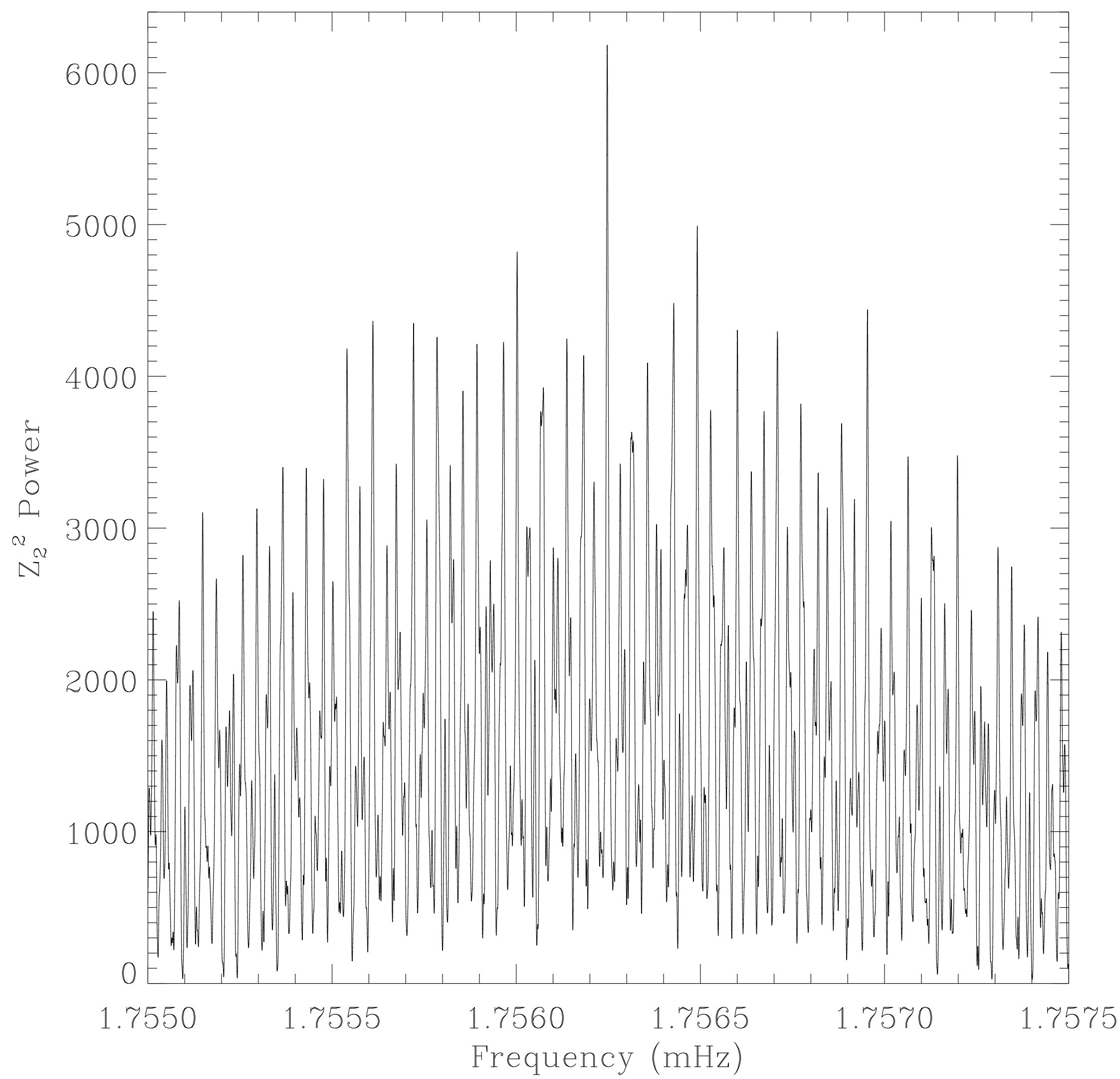

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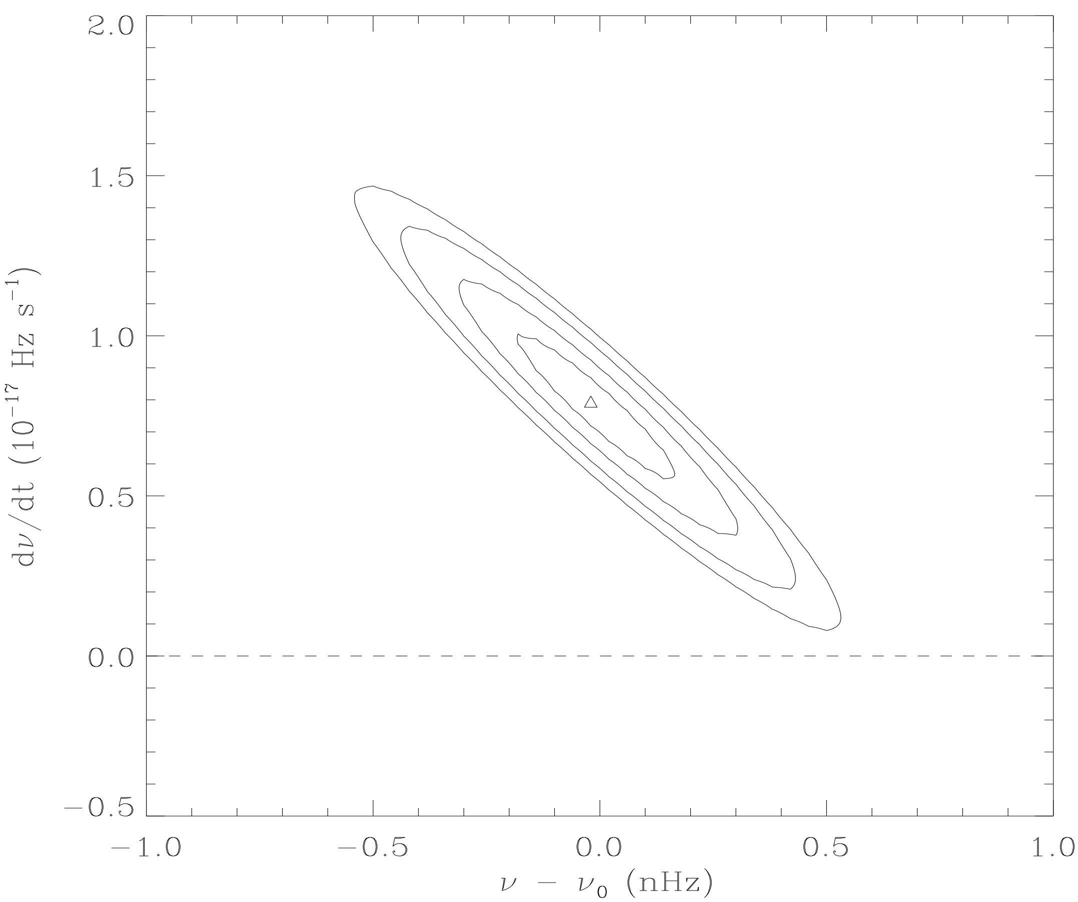

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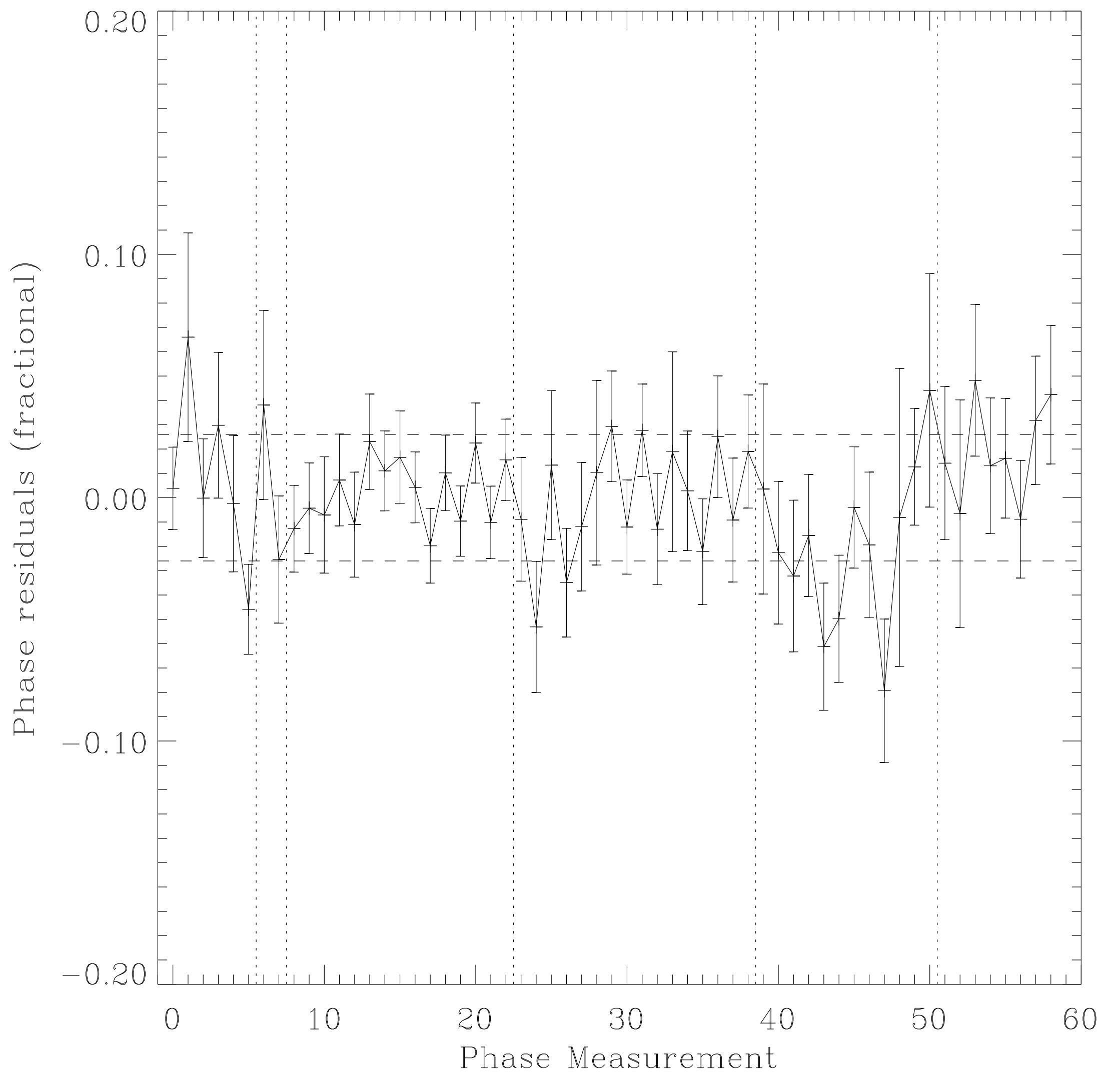

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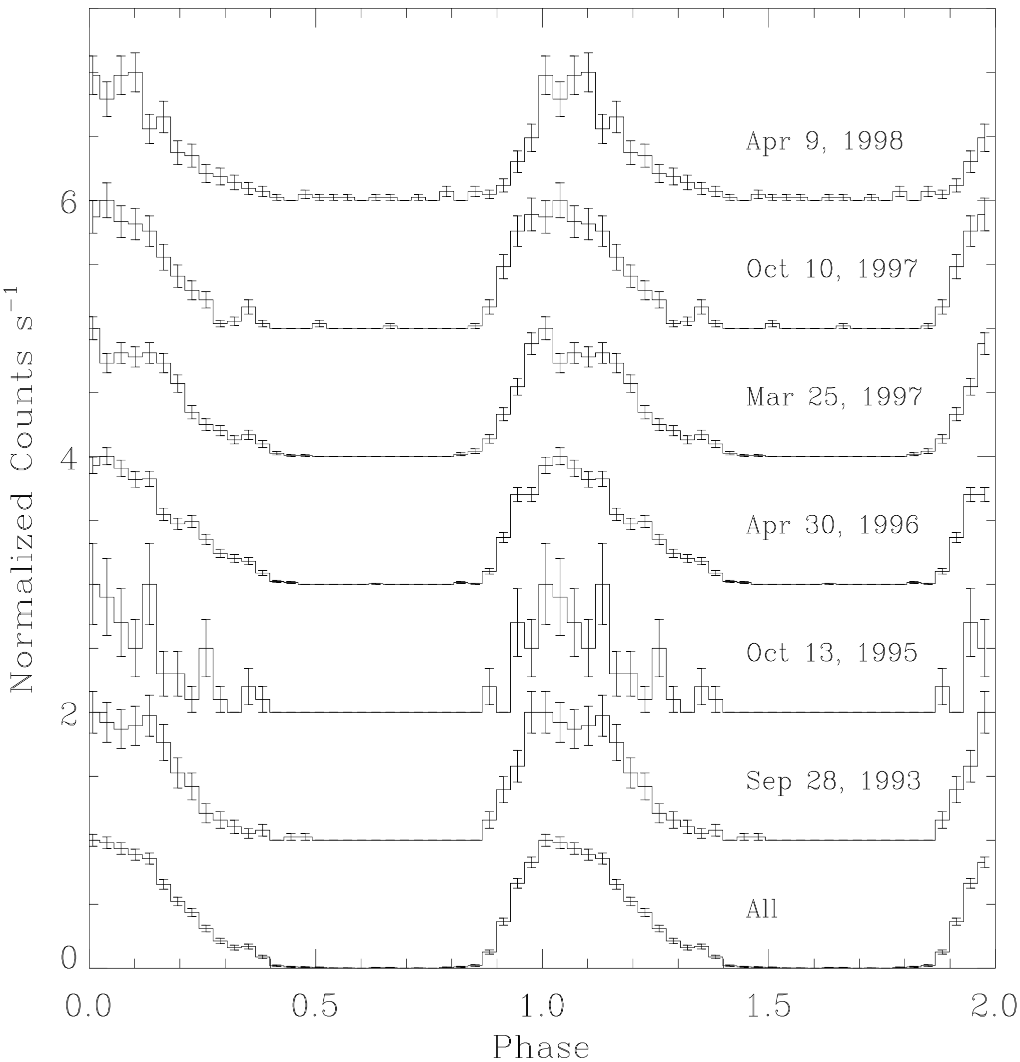

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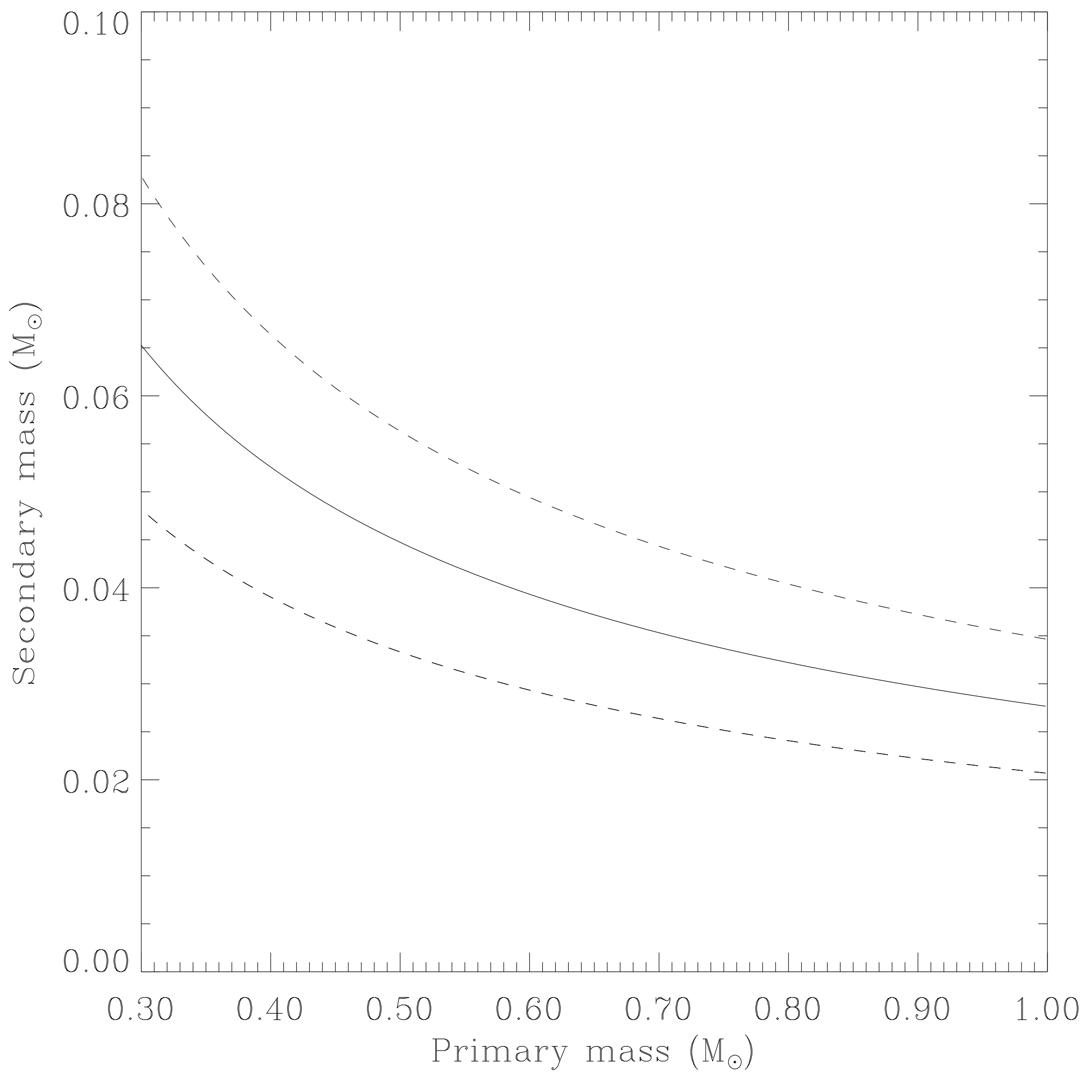

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Table 1: ROSAT and ASCA Observations of RX J1914.4+2456

OBSID	Instrument	Start UT	Stop UT	Exposure (ks)
300337	PSPC	Sep 28, 1993	Sep 29, 1993	7.0
300509	HRI	Oct 13, 1995	Oct 13, 1995	2.4
300509	HRI	Apr 30, 1996	May 5, 1996	25.9
300587	HRI	Mar 25, 1997	Mar 28, 1997	19.4
300337	HRI	Oct 10, 1997	Oct 11, 1997	21.7
36007000	SIS	Apr 9, 1998	Apr 10, 1998	21.4

Table 2: Timing Solution for RX J1914.4+2456

Model Parameter	Value
t_0 (TDB)	49257.5333731 (MJD)
ν (Hz)	0.0017562465(2)
$\dot{\nu}$ (Hz s^{-1})	$0.8(3) \times 10^{-17}$